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PERCEPTION OF SPATIAL FEATURES WITH STEREOSCOPIC DISPLAYS.(U)

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PERCEPTION OF SPATIAL FEATURES WITH STEREOSCOPIC DISPLAYS

Summary Progress Report

Covering the Period 1 September 1979 through 31 August 1980

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I INTRODUCTION

A. Background

At the beginning of this project year, our plan was to review the literature pertaining to stereo display systems, binocular vision and stereopsis, and the interaction of the observer with the display system in order to determine which major display system variables warranted closest and most immediate study.

Upon delving into the literature, we found that, very often, no distinction is made between systems that require stereopsis and those that do not. Consequently, it is first necessary to categorize existing displays into those that require the viewer to observe the display with both eyes and those that transmit the same information to the observer even when viewed monocularly. As an example of the latter, many video systems, which reportedly portray three-dimensional images, in fact present a single two-dimensional image to the observer and require him to infer the third dimension from such factors as motion parallax, perspective, and texture gradients in the image on the screen. Hence, video displays of this type do not fall into the category of three-dimensional imaging systems, but rather into pseudo-three-dimensional displays.

In contrast, a true stereo video display, however, is one that requires binocular vision for the synthesis of the third dimension, typified by the MEGAVISION® system.* This system consists of PLZT electrooptical shutters placed before the eyes and synchronized with the field interlace of a video system. When activated, the MEGAVISION® system allows the left eye to see one set of scan lines and the right eye to see another set of scan lines on the same video screen. If these two fields are generated in such a manner as to produce binocular parallax, then the observer sees a three-dimensional image. The principal investigator has observed such a display system in operation at the 23rd Annual International Technical Symposium and Instrument Display sponsored by the Society of Photo-optical Instrumentation Engineers, at San Diego, California, 27-30 August 1979 and found the impression of depth to be compelling. This stereo display system has the additional capability of portraying three-dimensional scenes in full color.

Among stereo displays, another distinction that is potentially important for the purposes of this study is whether individual images

*MEGAVISION® is a product of the Megatek Corp., 1055 Shafter Street, San Diego, California 92106.

must be presented to each eye, as in a stereogram (haploscopic displays), or whether parallax caused by intraocular distance is sufficient to generate the impression of a third dimension (holographic displays). During the course of this study, the principal investigator has observed stereo displays of both types. The first type is typified by the MEGA-VISION® system, which uses electrooptical shutters to isolate the image transmitted to each retina; separation of stereo images can also be accomplished through plane polarization, by chromatic filtering, and prismatically (as in lenticular viewing screens). The second type is typified by the hologram, which permits free viewing of a single image. Another stereo display of this type is the Space Graph®,* which uses an oscillating mirror to generate the third dimension. The principal investigator has experienced both types of stereo displays, and thus has firsthand information concerning the advantages and shortcomings of each type.

From the foregoing, it is apparent that we can organize three-dimensional display systems into the following categories: pseudo-three-dimensional, holographic, and haploscopic. Each of these categories is affected differently by degradation of the physical (display) and physiological (human) factors of the image.

- In the case of pseudo-three-dimensional displays, physiological conditions such as aniseikonia (differences in retinal image size in the two eyes) are of little significance because only monocular perception of the display is required for complete acquisition of image information. Furthermore, because only one image is presented on the display, it is nearly impossible for physical factors to produce dissimilar retinal images.
- In the case of holographic displays, physiological factors play an important role in determining three-dimensional image quality, because binocular perception is essential for properly perceiving this type of display. Consequently, any reduction in binocular perception as a result of such factors as aniseikonia, uncorrected refractive errors, or phorias results in reduced stereopsis. However, because holographic displays present essentially a single image to the viewer, physical characteristics of the image *per se* cannot affect the quality of three-dimensional imaging.
- Physiological factors are as important in the case of haploscopic three-dimensional displays as in the case of holographic displays, but physical display characteristics also become critical. Because separate images are presented to each eye, the quality of each image must be properly matched if adequate stereopsis is to be maintained. Indeed, it is only in haploscopic displays that the concept of the physical factors affecting binocular

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*Space Graph® is a product of Bolt, Beranek and Newman, Inc., 50 Moulton Street, Cambridge, Massachusetts 02138.

retinal-image quality really has any meaning. Information in the body of this report concerning the physical factors affecting image quality in three-dimensional display systems thus pertains most particularly to haploscopic displays. This report also outlines information concerning the physiological variables that affect the quality of three-dimensional displays, which has a bearing on both haploscopic and holographic display systems.

The interaction of physical and physiological variables has been found to affect performance of three-dimensional imaging systems in subtle, and sometimes not so subtle, ways. Our progress in the three major areas of research--physical factors, physiological factors, and interaction effects--is outlined in subsequent sections.

B. Research Emphasis

At the outset of the project, the SRI binocular eyetracker/stimulus deflector system was configured in such a way as to permit us to evaluate physiological factors more readily than physical factors. Consequently, our initial research efforts involved a reevaluation of the way in which the observer's visual system gathers, analyzes, and incorporates information from three-dimensional display systems. Many of our early studies in this field used selectively stabilized images to probe the effects of isolated physiological factors.

As the project progressed, our attention turned progressively toward evaluation of the physical variables of three-dimensional displays. By the end of the past year, nearly all our efforts were concentrated in this area. During the next project year, most of our studies will focus upon the physical aspects of three-dimensional display systems that may affect the efficacy with which such displays accurately portray the third dimension.

II PHYSIOLOGICAL VARIABLES

Since the beginning of this project year, our research methods have evolved into a program that we call "selectively stabilized images." This research has evoked much interest wherever it has been presented. Our initial results were presented at the European Conference on Visual Perception in Noordwijkerhout, The Netherlands, in October 1979 (Piantanida and Crane, 1979). Subsequent studies have filled in some of the gaps that were apparent at that time, and more comprehensive reports were presented at the Topical Meeting of the Optical Society of America and the Oculomotor Symposium 80 (Piantanida and Crane, 1980a;b). We have also submitted a manuscript for publication in a volume entitled Oculomotor Symposium 80. A copy of that manuscript will be sent when reprints become available.

Interest in selectively stabilized images has been generated by our desire to understand two common phenomena that significantly affect stereopsis: "suppression" and "filling in." Suppression is a phenomenon that occurs very frequently in binocular vision; it involves the lack of perception of features actually present in a retinal image. The case of interest here is where the same feature is present in the two retinas but at different locations. This disparity of location leads to the perception of depth, but simultaneous perception of both retinal images would result in diplopia. The absence of diplopia implies some combination of fusion of the two images or suppression of one or both of them.

Fusion is most evident in symmetrical situations where the retinal image of a single feature in the scene falls on opposite sides of the two foveas. For small disparities, the observer still perceives the object on the midline, and it seems that neither retinal image per se reaches awareness. Thus, although both retinal images are suppressed, a single image is nonetheless perceived. This percpetion probably results from the visual (cortical?) mechanism we call fusion. However, such symmetry is rather contrived and represents a synthetic representation of the visual world as often occurs in the laboratory.

In the more common real-world event, where an image of a particular feature or part of a feature in the field exists on only one retina (because of persepctive, parallax, or interposition effects in the other retinal image), that feature reaches perceptual awareness while the image on the corresponding point of the other retina is suppressed. The feature is then seen in a position that corresponds to its retinal image position; thus it is unnecessary to invoke a fusion mechanism to account for its perception.

It seems, then, that in either of the two situations described above, suppression is potentially important for preventing diplopia. But if an awareness of suppression itself reached consciousness, the unity of our perception of the visual scene might be disrupted--just as it might be if the absence of perception in scotomas and the blind-spot region of the eye reached awareness. We think that the visual system has a mechanism for preventing perceptual awareness of suppression, that the mechanism is observable in the phenomenon of filling-in, and that study of the filling-in phenomenon may lead to a better understanding of the phenomenon of suppression, which seems such an integral part of binocular perception.

Two factors suggested the use of the selectively stabilized image technique as a means to explore suppression and filling-in: the similarity of stabilized image disappearance to visual suppression, and indications that the information for the filling-in of suppressed areas is provided by retinal signals from unsuppressed edges nearest the suppressed area. Consequently, we elected to stabilize certain parts of the image to simulate suppression and to control the edge information present on the retina by selectively destabilizing other parts of the retinal image.

The apparatus that we use for our selectively stabilized image studies consists of a binocular pair of two-dimensional eyetrackers and a pair of

stimulus deflectors through which the subject views the stimuli. The horizontal and vertical eye-movement signals from each eyetracker can be used to drive the horizontal and vertical deflecting mirrors of its corresponding stimulus deflector. By adjusting the gain between the eyetracker and its stimulus deflector, it is possible to undo any of the retinal image motion produced by normal eye movements. Thus, complete retinal image stabilization is possible.

Stimuli that are to be imaged on the retina without stabilization are placed in the stimulus deflector at a plane conjugate to the retina, so the observer always sees objects in this plane as being sharply focused. However, because they are proximal to both the vertical and horizontal deflector mirrors, objects placed in this plane produce retinal images whose motion cannot be undone by our stimulus deflector system; i.e., they move about on the retina the way retinal images normally do.

Because the stimulus deflectors are driven electronically by the eyetracker output signals, it is easy to change the gain between these two subsystems. For example, if the gain between the eyetracker and the stimulus deflector were set to zero, the retinal image motion produced by normal eye movements would be the same as in free viewing conditions. If the gain were set at 0.9, an eye movement that displaced the retina 1-mm horizontally would displace the retinal image 0.9-mm horizontally in the same direction. A gain of 1 would produce complete image stabilization, so that a movement that displaced the retina by 1 mm would also displace the image by 1 mm, causing the image to remain permanently fixed on the retina. Gains above 1 are also achieveable; if, for example, the gain were set to 1.2, an eye movement that resulted in a retinal displacement of 1 mm would displace the retinal image 1.2 mm. Our research in selectively stabilized images almost always uses a gain of 1 on both the horizontal and vertical channels; the use of gains other than 1 is discussed further in the section considering isolation of inputs to stereopsis.

The studies reported in this section deal almost exclusively with physiological variables of binocular vision. However, they were conducted simultaneously with investigations of three-dimensional display system parameters and interactions of display systems with physiological variables. Consequently, the rationale for conducting specific physiological studies may not be readily apparent, as the impetus may have come from one of the other areas. For example, our investigation of selectively stabilized binocular images has indicated that chromatic information and achromatic information in three-dimensional displays are not involved in human stereopsis in the same way. This finding, in turn, has led us to investigate differences between chromatic and achromatic edge information in the human visual system. Because of the need to organize the report of our research efforts into major categories, rather than to present a chronological account, continuity within a particular research area may not always be readily apparent.

A. Monocular Effects

1. Achromatic Stimuli

Our earliest investigations concentrated on monocular factors that may affect perception and performance of binocular display systems. Because subsequent study has indicated a difference between chromatic and achromatic stimuli, this dimension has been considered an important variable in understanding inputs to both monocular perception and stereopsis. The first stimuli we used were simple achromatic monocular patterns that could be stabilized to disappearance with only compensation of horizontal retinal image motion. A typical stimulus consisted of a vertical black bar on a white background; the bar extended out of the field of view at both the top and bottom. Because the field of view was approximately 25 degrees and the edge of the field was everywhere diffuse (because it was not presented in a plane conjugate with the retina), there was very little edge information at that boundary. Furthermore, since that boundary provided the only interface between stabilized and unstabilized features in the field, there was essentially no edge information that could be used for filling-in across the field once the retinal image had been stabilized to disappearance. Thus, when the black stripe disappeared, the field of view appeared uniformly gray. The perception was neither of the blackness of the bar, nor of the whiteness of the background, but of some intermediate level.

Because we had assumed that edges would have a profound effect upon the perception of stabilized images (because of the similarity of these edges to those of scotomas and the blind spot), we introduced perceptual edges by placing unstabilized occluders in the stimulus deflector at the plane conjugate with the retina. When next we presented a stabilized black bar on a white background, edges of high luminance contrast (unstabilized vertical black edges on both sides of a white field) were visible in the field even when disappearance of the black bar had occurred because of stabilization. When disappearance of the black bar occurred, the background field assumed a lightness much greater than in the previous experiment. We surmised that this increased lightness of the field was due to the large luminance contrast at the unstabilized boundaries. This perception of increased lightness propagated across the field in much the same way as the filling-in phenomenon occurs. Note that upon disappearance of the black bar, the field appeared lighter--despite the fact that the total area of retinal illumination was smaller than it had been in the previous case, where no unstabilized occluders had been present. The consistency of this observation across observers has revealed the efficacy of unstabilized edges in modifying the perception of regions in visual space in which the corresponding retinal-image signal does not reach perception.

To examine the role of edges in filling-in across perceptually suppressed areas of the retina, we generated a series of stimuli designed to produce conflicting information. The first such stimulus consisted of a black square on a white background (viewed without unstabilized occluders), but with only vertical stabilization of the retinal image.

This type of selective stabilization was produced by opening the link between the eyetracker and the horizontal stimulus deflector mirror. Before disappearance of the stabilized horizontal edges of the black square, observers saw a uniformly black square upon a white background. Upon disappearance of the upper and lower edges of the black square, because of stabilization, the vertical edges of the square remained, producing two, high-contrast luminance edges but no object between them. In some subjects, this perception was resolved into a figure consistent with the edge information present--that is, a vertical hourglass figure.

Here again, filling-in produced perception consistent with the information available at the only edges visible within the field. It should be noted that not all observers saw this figure, and perception of it depended upon such factors as whether the observer used his or her dominant or nondominant eye, and the region of the square that was fixated. This pattern of filling-in was repeated throughout our studies of conflicting edge information at achromatic boundaries, whether those boundaries consisted of single or multiple edges.

After these studies, our attention turned to achromatic stimuli that we stabilized both horizontally and vertically. A typical figure was a stabilized black disc seen on a white background. With no unstabilized edges visible in the field, the entire black disc disappeared, resulting in the perception of a uniform gray field. However, when an unstabilized vertical black bar was placed across the center of the field so that its edges always intersected the stabilized edges of the black disc, disappearance of the black disc resulted in conflicting edge information. Where the unstabilized black stripe crossed the white background field, we would expect high contrast edges to be always visible. Where the unstabilized black stripe crossed the stabilized black disc, retinal contrast should be very low but perceptual contrast should be high. Preliminary results indicated that this conflict was resolved differently in different parts of the retina. Occasionally, some parts of the stabilized black disc would reappear independently of others. When they did, they determined the perceived local contrast in the part of the field where they were visible. However, when the portion of the black disc present in one part of the field was invisible, the perceived luminance contrast of that part of the field was determined solely by the unstabilized edge of the vertical black bar. These results suggest the possibility of interjecting local retinal luminance contrast signals that do not reach perceptual awareness to modify perception of adjacent areas that do reach perceptual awareness.

One of our most recent studies in monocular perception of selectively stabilized stimuli involved the alteration of lightness perception of unstabilized achromatic stimuli by the disappearance of a luminance contrast step in the background upon which the stimuli were perceived. In one of our experiments, two small gray squares were viewed in normal unstabilized vision upon a background consisting of a stabilized black and a stabilized white rectangle, respectively, which in turn were placed on an unstabilized gray surround field. Disappearance of the black and white backgrounds results in a profound change in perception

of the two unstabilized gray target squares. The target square falling upon the stabilized black background turned white, and the target square falling upon the stabilized white background became black. This compelling result, similar to the findings of Yarbus (1967), clearly indicates that retinal contrast, even in the absence of any perceptual contrast, is capable of modifying the perception of unstabilized images elsewhere on the retina.

These monocular achromatic studies raise two intriguing possibilities: first, that edge information *per se* may be used to generate perception inconsistent with retinal image information, and second, that these percepts may interact with real retinal images in the other eye to produce stereopsis. Our program for the next year will study the question of whether edge information presented to only one eye is sufficient for supporting stereopsis when whole-image information is presented to the other eye.

2. Chromatic Stimuli

Coincident with our studies of achromatic stimuli, we examined the monocular effects of chromatic edges upon the perception of selectively stabilized images. One of our earliest chromatic experiments involved a replication of the Krauskopf (1963) effect, in which a stabilized disc of one color is viewed upon a background disc of another color. For example, if an unstabilized red disc is placed on a black background, and a stabilized green disc is imaged within the unstabilized red disc, upon disappearance of the stabilized red/green boundary, the entire field becomes red. This is consistent with the chromatic contrast information available at the outer unstabilized edge of the field.

To test the hypothesis that it is the chromatic contrast at the unstabilized edge that provides the information for filling-in the stabilized area, we inverted the stimulus array as follows: As before, a stabilized green disc was superimposed upon an unstabilized red surround, but now the red surround extended to the diffuse limits of the field. In addition, an unstabilized black disc was superimposed within the stabilized green area. Thus, the only unstabilized edge visible in the field was at the boundary between the black disc and the green area. In this case, upon disappearance of the stabilized red/green boundary, the entire field appeared green. This is again consistent with the hypothesis that, with stabilized disappearance, perception may be determined by filling-in rather than by local retinal contrast.

In both the "inside-out" and "outside-in" Krauskopf experiments noted above, there was chromatic filling-in but no conflict was created in the filling-in process. A conflict was produced, however, when we attempted to create the inside-out and outside-in Krauskopf effects simultaneously. In this experiment, a stabilized green disc was again placed on a red background; in addition, an unstabilized black disc was placed inside the green disc and an unstabilized black region surrounded the red area. In this case, upon disappearance of the red/green boundary,

red information propagates inward from the outer black/red boundary, and green information propagates simultaneously outward from the inner green/black boundary. The net result, for most subjects, was the perception of an achromatic, i.e., gray, annular zone between the areas of heightened chromatic contrast at the unstabilized edges.

A different perception occurs when the same chromatic conflict situation is set up in a one-dimensional analog. In this case, the subject views a red/green bipartite field with the (vertical) red/green boundary stabilized; the field is viewed through unstabilized occluders, which in effect places unstabilized black edges at the left and right sides of the field. Upon disappearance of the vertical red/green edge, red information propagates righthand from the lefthand black/red edge, and green information propagates leftward from the righthand green/black edge, producing conflicting chromatic information at the stabilized boundary. As we have confirmed numerous times during the past year, this conflicting chromatic information was resolved in a number of different ways by different observers. Some observers report a simultaneous occurrence of both colors, i.e., the "forbidden" reddish green; others report an indescribable color; while some see this area as achromatic. These results suggest that the filling-in phenomenon is quite basic to vision and may be capable of producing percepts previously though to be impossible. Furthermore, the results suggest the possibility of adding color to a three-dimensional display by providing chromatic edge information to only one or the other of the retinal images.

In addition to these experiments, we examined the chromatic analog of the luminance experiments we had conducted, some of which were described earlier. These include vertical stabilization only of a square of one color seen on a background of another, vertical stabilization only of a horizontal bar of one color seen on a background of another color, and the Yarbus effect. The results and conclusions were similar to those drawn from the luminance experiments, in that we found both chromatic and achromatic perceptions that were inconsistent with the chromatic information present on the retina. In addition, the chromatic analog of the Yarbus effect confirmed that not only can the luminance of unstabilized targets be profoundly changed by disappearance of a luminance edge in the background, but the color of unstabilized targets can be drastically changed by disappearance of a chromatic edge in their background. These findings heighten the possibility of generating a three-dimensional display system in which both color and brightness may be modified by retinal signals that do not reach perceptual awareness.

B. Binocular Effects

Our initial studies in this area consisted of simple experiments to test whether the images of objects viewed binocularly would disappear when they were stabilized simultaneously on both retinas. Observers viewed objects through both stimulus deflectors while the eyetrackers monitored both horizontal and vertical motion of both eyes. Early stimuli used to assess binocular disappearance included cross-hair

bulls-eye targets. Both of these simple targets consisted of fine black lines on a white background, and both disappeared during binocular stabilization. We then presented real, three-dimensional objects and found a similar result: perception of the object ceased when its image was stabilized on both retinas.

In earlier studies we had determined that flickering the source of illumination of objects whose images were stabilized on the retina would not result in a reappearance of the object if the flicker were above approximate 5-10 Hz. We tested whether sinusoidal flicker in each eye would restore perception of binocularly stabilized images: We found that, like monocular images, binocularly stabilized images are not affected by flicker at frequencies above 5-10 Hz, irrespectively of whether the flicker is in-phase or out-of-phase in the two eyes. In addition, the flicker technique suggested a means of evaluating the persistence of depth perception during binocular disappearance. This technique will be discussed in a subsequent section.

1. Monocular Disappearance: Achromatic Stimuli

The experiments described in this section were designed to assess the possibility of depth perception during monocular disappearance of a stabilized image. An early experiment involved fusion of random dot stereograms followed by stabilization of the retinal image of one of the stereo pairs. Observers reported that disappearance of the stabilized image of one of the stereo pairs resulted in the loss of both depth and perception of the embedded figure.

Subsequent experiments involved extended-object stimuli, which generate global depth effects rather than the local depth effects generated by random stereograms. A typical stimulus configuration for these experiments consisted of a pair of unstabilized occluders which, when fused, formed a window through which an achromatic stimulus could be viewed by the observer. The stimulus seen through the unstabilized occluders (window) could be stabilized on one or both retinas. In a typical situation, the left retinal image of a black bar was stabilized on a white background. The right retinal image of the black bar was not stabilized, and therefore could be moved about on the retina by moving the mirrors of the right stimulus deflector. For each observer in this study, a pilot experiment was run in which neither retinal image was stabilized. The observer viewed the stimuli in normal unstabilized vision, moved the occluders so that they were fused, and then moved the images of the black bar so that they, too, were fused. The resulting percept was of a single black bar seen through a single aperture. Under these conditions when the image of the black bar was moved laterally on the right retina, the observer reported the black bar moving in depth.

The next experiment involved stabilizing the image of the black bar on the left retina to disappearance, and again moving the right retinal image laterally. Under these conditions observers continued to report

the observation of motion in depth of the black bar. This was the first instance in which we observed the preservation of depth perception despite the loss of monocular perception of the object.* We also noted that because the image on the left retina was fixed at a constant position while that on the right was not, spontaneous vergence movements of the observer's eyes also resulted in the perception of motion in depth of the black bar. We have subsequently used this observation to test the interaction of normal inputs to stereopsis. These experiments are reported in a subsequent section.

2. Monocular Disappearance: Chromatic Stimuli

Having found that chromatic and achromatic displays affect suppression and filling-in differently, we evaluated the possibility of similar differences in stereopsis. The major difference between the stimulus configuration in this case and in the achromatic case was that the stimulus to be stablized consisted of an isoluminant chromatic array, rather than an array consisting of luminance gradients. Thus a typical stimulus configuration involved the same unstabilized occluders as before, which became visually fused and through which was seen an image consisting of a green bar on a red background. The chromatic portion of the display was rendered isoluminant by either subjective matching or flicker photometry. As in the achromatic experiments, the initial experiment involved fusion of the (green) bar without image stabilization and subsequent induction of lateral retinal image motion in the right eye. This resulted in the perception of motion in depth of the bar, although the magnitude of this depth effect was much reduced relative to that seen with achromatic displays.

Following this experiment, the bar was stabilized to disappearance in the left eye again. When the right retinal image was moved laterally, however, the observers now reported seeing the isoluminant portion of the display moving laterally, rather than in depth. Here again, then, we find a difference in the effects of chromatic and achromatic displays. It seems that isoluminant chromatic displays are capable of supporting stereopsis in the unstabilized condition, but not in the stabilized condition. It is our conjecture, however, based upon the findings of Lu and Fender (1972) and Richard Gregory (1977) with random dot isoluminant stereograms, that isoluminant chromatic patterns may not, in fact, support stereopsis even under unstabilized (i.e., normal) conditions. The reason that we observed motion in depth during the experiments in which the isoluminant display was unstabilized may be that it is virtually impossible to produce isoluminance everywhere on the retina simultaneously,

*To our knowledge, this is the first report anywhere of the preservation of depth with disappearance. We believe that further study of this and related phenomena will yield important insights into the stereoscopic mechanism.

in which case there are always some small residual luminance signals available to the stereopsis mechanism. The loss of stereopsis with stabilization of one retinal image may then be construed to mean that even the luminance signal to stereopsis is reduced by image stabilization, to the point that the combined luminance signal under these conditions is below the threshold necessary to support stereopsis.

3. Monchromatic Disappearance: Mixed Chromatic and Achromatic Stimuli

Our findings that chromatic and achromatic stimuli affect the persistence of stereopsis differently under stabilized conditions allowed us to explore conditions that produce conflicting input into the stereo system. The major question we asked was: If we present an array consisting of an isoluminance chromatic part and an achromatic part, and stabilize this array to disappearance on one retina, will lateral motion of this array on the other retina result in lateral motion, because of the presence of the isoluminant chromatic part, or motion in depth because of the effect of the achromatic part of the array? Or will the observer see the chromatic part of the display moving laterally and the achromatic part moving in depth? Our experiments indicate that the unity of the array is preserved at the expense of fidelity of motion perception. The display appears to move first in depth and then laterally along a curvilinear path.

4. Binocular Disappearance

Our most recent experiments on selective stabilization use stimulus arrays designed to evalute the possibility of depth perception during stabilization of both monocular images to disappearance. A major obstacle to achieving this condition had been the requirement that one or the other of the retinal images be able to be moved laterally in order to generate the perception of motion in depth. (During our monocular experiments when the unstabilized retinal image remained stationary on the retina, the depth plane specified by the image of the black bar was ambiguous. That is, observers could observe motion in depth, but did not appear to have static depth perception.) We have subsequently found two ways to circumvent this problem.

Earlier experiments that used sinusoidally flickering illumination of binocularly-viewed stimuli revealed that the flicker was evident even when the illuminated stimuli had disappeared because of stabilization. Furthermore, the flicker appeared to emanate from the plane occupied by the fused binocular stimulus. We used this observation to establish the following stimulus configuration: Observers viewed a binocularly stabilized stimulus through a pair of unstabilized occluders, which were visually fused. In the same plane as the unstabilized occluders, we positioned a fixation target in front of each eye so that the observer perceived these as a single, fused fixation point, which appeared to be in the same plane as the unstabilized occluders. When the stabilized

stimuli (usually a black bar on a white background) were presented to each eye in foveal fixation (so that the fixation point fell on the center of the black bar), the observers perceived before disappearance a single fused black bar lying in the same plane as the fixation point. By placing orthogonal plane polarizers in front of the two eyes and illuminating the stabilized stimuli through a rotating plane polarizer, it was possible to flicker the retinal image of the black bar on the white background in the two eyes. Our previous experience with this technique indicated that flicker frequencies above approximately 5-10 Hz did not interfere with the disappearance of the stabilized image. Thus, when the image of the black bar disappeared in both eyes, the observers reported perceiving a flickering field in the same plane as the fixation point.

Because we could independently control the position of the retinal image of the black bar on each retina, it was also possible to introduce retinal disparities, which could not be changed by eye movements, but which would alter the apparent depth of the black bar and the field on which it was perceived. For instance, when we positioned the images of the black bar nasally on each retina, observers reported before disappearance that the black bar was further from them than the fixation point. When the images of the black bar were flickered simultaneously in anti-phase, the observers reported that the flicker seemed to emanate from a plane further from them than the fixation point. When the image of the black bar disappared in both eyes, the source of the flicker continued to appear to emanate from a point beyond the fixation point. We believe that this indicates that the depth plane specified by the retinal disparity of the black bars persisted, although the black bar itself was not visible with either eye.

A second technique was similar to the first, except that the source illuminating the black bar was not flickered. The observer's task was to report the relative distance to the fixation point and to the plane where the black bar appeared. As in the previous condition, when the black bar was imaged with nasal disparity relative to the fixation point, it appeared further from the observer than the fixation point. When the image of the black bar was then stabilized to disappearance on both retinas, the depth plane in which this fused bar had been perceived persisted despite disappearance of the bar in both eyes. In other words, the observer continued to perceive the fixation point as closer than the empty, white background field.

Our observations that depth perception persists in the absence of object perception is consistent with the suppression model of stereopsis, in which portions of each retinal image may fail to reach perceptual awareness (thereby eliminating diplopia) yet appear to be sampled by the stereopsis system. These perceptually suppressed areas contain information about the relative retinal disparities of features in the retinal image, and this disparity information is used for producing depth perception. In other words, the portions of the retinal image that do not reach perceptional awareness are the very portions that are used by the visual system for producing stereopsis. Our rationale for using stabilized images in this study is based upon our assumption that disappearance of

the stabilized image mimics the normal mechanism of visual suppression. It would appear from our results that such an assumption is warranted, in light of the filling-in phenomenon and the persistence of stereopsis despite the cessation of perception of some features of the retinal image. This encourages our continued use of selectively stabilized images as a means to explore inputs to stereopsis that may not reach perceptual awareness.

III PHYSICAL VARIABLES

During part of the project year, the SRI eyetracker/stimulus deflector system was configured in such a way as to facilitate recording of an observer's vergence eye movements as he viewed a three-dimensional display. The output from the eyetracker was not linked to the stimulus deflectors, as it was in the experiments described in the previous section. Instead, the horizontal eye movement signals were recorded on either a 4-channel or 8-channel recorder. In addition, the horizontal output from the left eye was subtracted from the horizontal output from the right eye to obtain an eye vergence signal, which was recorded on another channel of the recorder. Because version eye movements are of the same polarity, the vergence channel produces zero output during pure versional eye movements. The vergence signal together with the signals from each channel could therefore be used to indicate when the subject was making vergence movements or version movements.

As in earlier experiments, observers viewed stimuli through the SRI stimulus deflector system but, the stimulus deflectors were driven not from the eyetracker, but by signals from a waveform generator. The frequency, waveform, and amplitude of the signals driving the horizontal channel in each stimulus deflector could be controlled by the experimenter. The motion produced at the horizontal deflection mirrors induced the perception of apparent motion of any objects viewed through the stimulus deflector system. If the DC offset of the deflectors was adjusted to allow fusion of the two retinal images, the observer would perceive a single object moving in space. If the polarity of the signals driving the two stimulus deflectors was the same, the observer would perceive a single object moving laterally in his field of view. If the signal polarity to one stimulus deflector was reversed, the observer perceived a single object that moved in depth. By suitably adjusting the amplitude of the signals driving the two stimulus deflectors, it was possible to generate a display in which the observer perceived a single object moving in depth along the midline.

Pilot studies indicated that for the stimuli of interest, the waveform, frequency, and amplitude that best met our needs was an 0.2-Hz sinusoid that moved the retinal image of the stimulus one degree peak-to-peak. When the stimulus deflectors were driven in antiphase, this waveform produced a readily apparent motion in depth of the stimulus object,

while allowing the two images of the stimulus object to remain fused throughout the entire excursion. Waveforms other than sinusoids were evaluated and found to produce more diplopia than sine waves, as did higher frequencies and amplitudes of sine wave oscillation.

Images viewed through the stimulus deflector system were presented on a rear projection screen located 60 cm from the last element of the stimulus deflectors. The focal length of the stimulus deflectors was adjusted to compensate for any spherical error in the observer's vision and to place the rear projection screen at optical infinity. The apparatus used for projecting the images on the screen consisted of a Kodak 650H Carousel® projector that had been modified to include a limiting aperture in the film plane. A right angle prism was positioned in front of the projector lens with its hypotenuse approximately along the ray path. The prism thus acted as a beam divider, resulting in the projection of two images on the screen. The prism could be moved laterally in the projection beam to balance the luminance of the two images on the screen. Orthogonal plane polarizers (Polaroid HN32) were positioned immediately after the prism so that the two beams that diverged from that point were orthogonally plane polarized. Both beams then passed through a common plane polarizer that was rotatable. Consequently, the intensity of the two beams could be varied inversely by rotating this plane polarizer. Neutral density filters could be placed either between the projection lens and the prism, or in the plane occupied by the orthogonal plane polarizers, in order to attenuate both beams or one beam with respect to the other, respectively. Each two-by-two slide placed in the projector produced two images on the rear projection screen. Each image was located on the screen in such a way that the observer viewed only one through each stimulus deflector system.

Images projected on the screen consisted of dark on light regular geometric figures (usually squares or rectangles) in a graded series of contrast. The nominal contrast of these slides were 20, 40, 60, 80, and 100 percent. Proper orientation of the two images on the screen was accomplished by rotating the beam-dividing prism about the ray path. With proper adjustments, the observer could easily fuse the images seen through the stimulus deflectors.

With the apparatus configured in this manner, it was possible to measure changes in the perception of motion in depth during systematic variations of stimulus parameters along several dimensions. Subjective measures of the perception of motion in depth were taken simultaneously with objective measures of eye movements associated with such perception, i.e., vergence movements.

Our initial studies evaluated several psychophysical methods for obtaining reliable and reproducible subjective measures of perception of motion in depth. It was our desire to generate a psychometric function capable of demonstrating systematic changes in perception of motion in depth with modifications of each stimulus parameter. We initially adopted a two-alternative, forced-choice procedure that required the observer to decide whether the perceived motion of an object at any given time was

characterized more accurately by axial or lateral motion. However, our observations indicated that this procedure resulted in a rapid transition from axial-motion responses to lateral-motion responses. Because these transitions did not occur at similar values of the stimulus parameter across observers and within observers over time, the procedure of sampling large potential ranges of stimulus parameters with small incremental units became tedious. Consequently, we adopted another psychophysical method for estimating the transition between the perception of axial and lateral motion. We used a modified method-of-limits approach in which the observer used a three-position switch to indicate when the perceived motion of the stimulus object was exclusively axial, ambiguous, or exclusively lateral.

Our first studies evaluated the effect of interocular contrast upon the perception of motion in depth. (By interocular contrast, we mean the ratio of the luminances to the two monocular figures presented to the observer.) Data in this experiment are recorded as percent contrast, which is defined as the difference between the two monocular luminances divided by their sum and is related to the angle of rotation of the plane polarizer in the common projection beam by the simple relation

$$\text{percent contrast} = \sin^2 A - \cos^2 A \quad ,$$

where A is the angular rotation of the polarizer.

The typical procedure for evaluating the effect of interocular contrast on the perception of motion in depth is as follows: The observer was aligned with respect to the binocular eyetracker by a dental impression bitebar and two forehead rests, and viewed the stimuli through the left and right stimulus deflectors. The interocular contrast ratio of the two stimuli was set near 1, and the observer generally reported that the two stimuli were fused and the perception was of one object moving axially in his field of view. (He indicated this perception by moving his response switch into the axial mode.) The observer's horizontal eye movement signals and vergence signals were displayed on the chart recorder. The experimenter then slowly adjusted the plane polarizer to change the interocular contrast ratio. (In any given experimental session, the experimenter would reduce the luminance of either the left or right stimulus while simultaneously increasing the luminance of the other.) The experimenter continued to reduce the luminance of one of the stimuli until the observer reported that he perceived the stimulus moving only laterally in his field of view, which he reported by moving his response switch into the lateral mode. The experimenter recorded this threshold setting and then reduced the luminance still further to ensure perception of lateral motion only. The experimenter then reversed the rotation of the polarizer to increase the luminance of the same stimulus until the observer indicated the perception of only axial motion in his field of view. The two end points record the extremes of the range in interocular contrast that produced ambiguous motion of the fused stimuli. Ten trials were conducted in this manner, and the observer was then permitted a brief

rest period. After the rest, the stimulus that was initially increased in luminance in the ten preceding trials was reduced in luminance for the subsequent ten trials. Thus, at the end of an experimental session, four data cells were filled. These can be used to calculate the percent contrast resulting in perception of only axial motion or only lateral motion when either the stimulus to the left eye or to the right eye is reduced in luminance.

The effect of interocular contrast ratio was evaluated for five levels of stimulus contrast. (Note that stimulus contrast here refers to the luminance ratio between a figure and its background. This is independent of the interocular contrast ratio.) Our studies have examined the effects of stimulus contrast percentages of the following nominal values: 20, 40, 60, 80, and 100 percent. Our studies have also examined the effects of absolute luminance level upon the perception of motion in depth with variations of the interocular contrast ratio at each of the five levels of stimulus contrast.

Our results show the following trends: A stereo pair of images is a compelling stimulus configuration that results in the perception of motion in depth over nearly the entire range of interocular contrasts. It is only when interocular contrast exceeds 90 percent (and in most cases 95 percent) that the observer perceives only lateral motion in the stimulus array. These results seem to be at least partially dependent upon the average luminance level of the binocular stimuli, as stimuli presented at higher luminance levels require higher interocular contrasts in order to completely eliminate the perception of motion in depth. Eye movement records obtained during the transition from ambiguous motion to purely lateral motion show a coordination of the physiological and psychophysical end points. Vergence movements cease at the approximate interocular contrast ratio of the transition from ambiguous to purely lateral motion.

The opposite end of the ambiguous region is more poorly defined; that is, the transition from perception of ambiguous motion to perception of purely axial motion occurs over a wider range of interocular contrast ratios than does the transition from ambiguous to purely lateral motion. This increased variability is found both within and across observers. Superimposed on this variability is a trend toward interocular contrast ratios closer to 1 for the transition from ambiguous to purely depth motion at both high and low stimulus contrast ratios. Stimuli with contrast in the range 40 to 80 percent appear to support the perception of pure motion in depth at higher interocular contrast ratios. We intend to explore this phenomenon more fully in our subsequent studies, with an eye toward defining stimulus variables that reduce the range of ambiguous-motion perception.

In contrast to the transition from ambiguous to purely lateral motion, the transition from ambiguous to purely axial motion shows markedly reduced correspondence between psychophysical judgments of the transition and physiological evidence thereof. The vergence records of

observers often showed no perceptible changes at the interocular contrast ratios that produced the perceptual transition. However, there were changes in the proportion of vergence to version movements at higher interocular contrast ratios. Thus, as we proceeded from higher interocular contrast ratios (which tended to produce perception of lateral motion only) to lower interocular contrast ratios (which tended to support the perception of axial motion), the transition from version movements to vergence movements frequently occurred before the observer signaled that he was seeing the stimulus moving only in depth. Consequently, the physiological indications of depth perception occurred at higher interocular contrast ratios than did the psychophysical. There may also be increased correlation of the physiological and psychophysical measures at higher luminance levels of the stimulus. Our subsequent studies will explore the variable of absolute luminance level more fully.

IV INTERACTION OF PHYSIOLOGICAL AND PHYSICAL VARIABLES

Among the most interesting of our results thus far have been some unexpected but potentially important interactions between observer variables and stimulus variables. Two types of interaction were found that have an effect upon a given observer's perception of the three-dimensional display, but certain subtle differences between the forms of the interactions require further exploration. One type of interaction is a result of observer-induced modifications of the two retinal images; the other form of interaction is a result of certain observer characteristics. Both types of interaction are reported in the following sections.

A. Inputs to Stereopsis

During our evaluations of selectively stabilized binocular images, when one of the retinal images was stabilized, observers often reported the perception of spontaneous motion in depth. The stimulus object was usually a black bar on a white background that was stabilized on one retina. When the gain between the eyetracker and the stimulus deflector was nearly correct, the observer's eye movements would result in very little retinal image motion in the stabilized eye and normal retinal image motion in the other eye. As a result, the observer's normal fluctuation in (version) eye movements produced corresponding changes in retinal disparity. We explored this effect because it seemed potentially important for understanding the effect of observer-produced changes in retinal disparity while viewing dichoptically presented stimuli (such as are found in helmet-mounted, heads-up display systems). A systematic analysis of the observer's eye movements and responses indicated that during spontaneous convergent eye movements, observers reported seeing the fused stimulus object approaching them, and that during spontaneous divergent eye movements, they reported the perception of recession of the object. From these data, it was impossible to conclude whether the vergence itself or dynamic retinal disparity accounted for the perception of motion in depth.

Our apparatus allowed us to explore the relative contributions of vergence and dynamic retinal disparity to stereopsis and the corresponding perception of motion in depth. We were able to do this by precisely controlling the amount of retinal disparity change produced by a given vergence movement. For example, if we stabilized both retinal images, then, by definition, eye movements could not produce any changes in retinal position and, therefore, no changes in retinal disparity. By setting the gain between the eyetracker and stimulus deflector at some value other than unity, different proportions of the normal vergence-induced changes in retinal disparity could be produced. Furthermore, by changing the offset of the stimulus deflector, it was possible to position the retinal images with any desired degree of static, or nominal, disparity.

We have made the following preliminary observations: Vergence-induced perception of motion in depth is much more effective when there is some static retinal disparity between the two images than when there is no static disparity. Furthermore, it is possible to reduce the perception of motion in depth by generating dynamic retinal disparities of polarity opposite to those that would normally be produced by a given eye movement. By way of illustration, consider the following: With the gain between the eyetracker and stimulus deflector set at zero, eye movements that displace each retina 1 mm will displace the retinal image by the same amount. At a gain setting of 0.5, an eye movement that results in a retinal displacement of 1 mm will displace the retinal image 0.5 mm. At gains up to 1, the displacement of the retinal image is always in the same direction as the image would move in normal viewing conditions. However, at gains greater than 1, the retinal image motion is opposite in polarity to normal retinal image motion. Under these conditions, then, the retinal disparity produced for any given vergence movement is opposite that which the visual system normally experiences. We have found that by suitably adjusting the gains, it was possible to cancel the vergence input to stereopsis by producing abnormal changes in retinal disparity. In other words, at critically defined gain settings, observers experienced a condition in which vergence eye movements produced no change in the perception of object depth: convergent movements no longer produced the perception of an approaching object, and divergent movements no longer produced the perception of a receding object.

These results have interesting implications for three-dimensional display systems. They imply that abnormalities of input to stereopsis through one of the normal physiological mechanisms may be offset by inputs to stereopsis through another physiological mechanism. Our subsequent studies on the development of a unique three-dimensional display system will examine this possibility.

B. "Observer" Variables

Our systematic study of three-dimensional-display system parameters has revealed some unexpected and striking effects of individual subject

variability ("observer" variables). The most important of these effects, in terms of the range of ambiguous motion perception produced by interocular contrast, is ocular dominance. Intuitively, we realized that ocular dominance might change the proportion of time that one or the other of the dichoptically presented visual stimuli was suppressed, but we failed to recognize the magnitude of the effect that this variable has upon the perception of motion in depth. When the observer was only mildly dominant in one eye, the ambiguous range of motion perception (between the perception of purely axial motion and purely lateral motion) was relatively small, although even this small range of interocular contrasts shows evidence of some change with ocular dominance. In particular, when the luminance of the dichoptic stimulus was reduced in the dominant eye, the cessation of the perception of motion in depth occurred at a higher luminance level (that is a lower interocular contrast level) than when the stimulus was reduced in luminance in the nondominant eye.

In observers with strong ocular dominance, the effect is much more striking. The range of interocular contrasts that results in ambiguous perception of motion in depth was significantly greater when the luminance of the stimulus was reduced in the dominant eye than when the luminance was reduced in the nondominant eye. In fact, for strongly dominant individuals the other extreme of the ambiguous range (the transition from ambiguous to lateral motion perception) may also occur at reduced interocular contrast ratios.

The evidence we have gathered so far on the effect of interaction between the observer and display indicates that at least one previously unexpected observer variable may have a profound effect upon the perception of motion in depth in three-dimensional displays. For example, in producing a three-dimensional display to be used by a single observer (for example, a cockpit display), it may be useful to be able to tailor the display to the ocular dominance of the observer. It is our observation that stimulus parameters that produce clear motion in depth in an observer with weak ocular dominance may produce ambiguous motion in observers who are strongly ocular dominant. Thus, without an awareness of the ocular dominance of the observer, stimulus parameters that seem normal may result in the perception of an ambiguous motion in depth. Therefore, we believe that it is necessary to include the effects of this observer variable, as well as others, in our subsequent studies.

V PLANS FOR THE FUTURE

Our studies have progressed toward an understanding of three dimensional display systems on three levels: physiological, physical, and psychophysical. We will continue to evaluate the effects of various physical variables (in isolation and in combination) upon depth perception. Our studies of physiological components will continue through the use of the selectively stabilized image technique and will concentrate on binocular stimulation, with either monocular stabilization or binocular stabilization.

We will attempt to develop a computer-controlled, three-dimensional display system upon which we may evaluate many of the factors we have found to affect stereopsis. For example, we expect to produce dichoptic stimuli in which only edge information is transmitted to one eye, and level information (including chroma) is transmitted to the other eye. This display system will also be capable of producing systematic changes in the display parameters that we currently find difficult to manipulate, such as continuous change of stimulus size. Toward this end, we have assembled the computing capability and hardware necessary for generating such a system and are generating software for its implementation.

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